DOE Fundamentals

ELECTRICAL SCIENCE

Module 5

DC Generators

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OBJECTIVES

TERMINAL OBJECTIVE

1.0 Given the type and application of a direct current (DC) generator, **DESCRIBE** the operating characteristics of that generator including methods of voltage production, advantages of each type, and voltage-vs-load characteristics.

ENABLING OBJECTIVES

1.1 **DEFINE** terminal voltage as it applies to DC generators.

1.2 **DEFINE** counter-electromotive force (CEMF) as it applies to a DC machine.

1.3 **DESCRIBE** the effects of commutation in a DC generator.

1.4 **STATE** the purpose of each of the following components of a DC machine:

- a. Armature
- b. Rotor
- c. Stator
- d. Field

1.5 **LIST** the three conditions necessary to induce a voltage into a conductor.

1.6 Using the left-hand rule of generators, **DETERMINE** the direction of the magnetic field, the motion of the conductor, or the direction of current induced into a conductor.

1.7 **DESCRIBE** how terminal voltage of a DC generator is adjusted.

1.8 **STATE** the basis behind each of the four DC generator ratings.

1.9 **LIST** the four internal losses found in a DC generator.

1.10 **DESCRIBE** the differences in construction between a shunt-wound and a series-wound DC generator with respect to the relationship between the field and the armature.

1.11 **DESCRIBE** the relationship between the shunt and series fields for cumulatively-compounded and differentially-compounded DC generators.

1.12 **DESCRIBE** the voltage-vs-load current characteristics for a flat-compounded, over-compounded, and under-compounded DC generator.

DC EQUIPMENT TERMINOLOGY

Direct current devices are used frequently in today's technology. Before the construction and operation of these devices can be introduced, a few common terms must be understood.

EO 1.1 **DEFINE** terminal voltage as it applies to DC generators.

EO 1.2 **DEFINE** counter-electromotive force (CEMF) as it applies to a DC machine.

EO 1.3 **DESCRIBE** the effects of commutation in a DC generator.

Terminal Voltage

Terminal voltage, as applied to DC generators, is defined as the voltage that can be measured at the output of the generator.

Counter-Electromotive Force (CEMF)

In a generator using a rotating armature, the conductors cut the magnetic lines of force in the magnetic field. Voltage is induced in the armature conductors. This induced voltage opposes the applied voltage; it counteracts some of the applied voltage, which reduces the current flow through the armature. This induced voltage acts counter to applied voltage; therefore, it is called *counter-electromotive force* (CEMF).

Applied Voltage

Applied voltage is defined as the voltage that is delivered across the load. This voltage should be the same as terminal voltage; however, various circuit faults and losses may reduce the terminal voltage.

Commutation

Commutation is the positioning of the DC generator brushes so that the commutator segments change brushes at the same time the armature current changes direction. More simply stated, commutation is the mechanical conversion from AC to DC at the brushes of a DC machine, as shown in Figure 1.

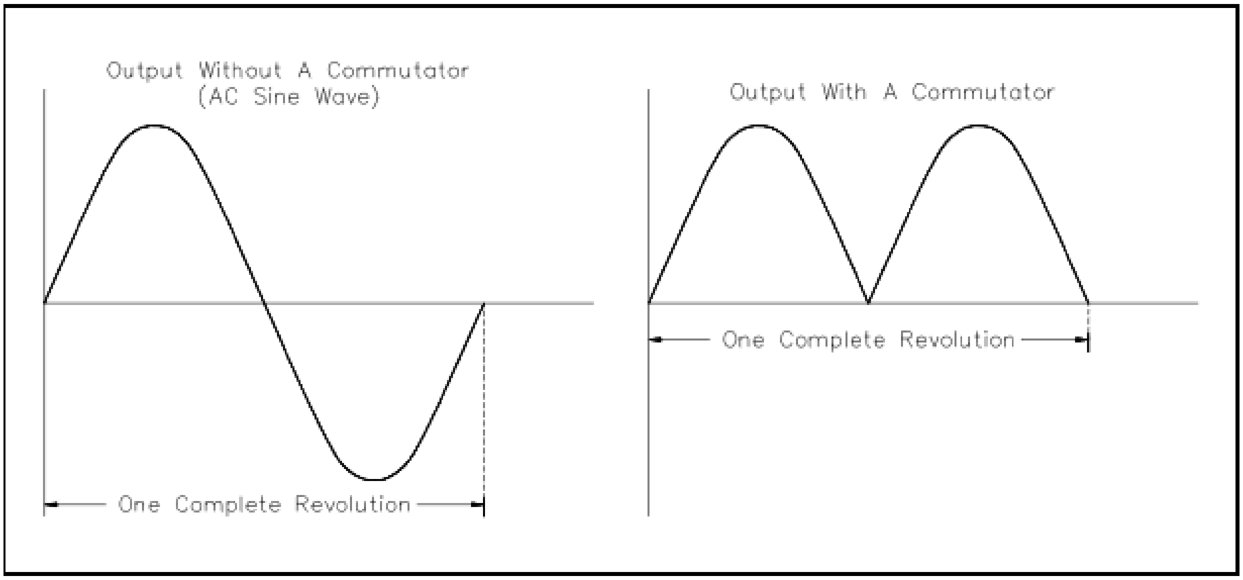

Figure 1 AC to DC Conversion with a Commutator

In a DC generator, commutation provides for the conversion of AC to a DC output that is generated in the armature windings. Commutation will be discussed in greater detail in subsequent chapters.

Summary

DC equipment terms are summarized below.

DC Equipment Terminology Summary

- Terminal voltage, as applied to DC generators, is defined as the voltage that can be measured at the output of the generator.
- Counter-electromotive force (CEMF) is defined as the induced voltage that acts to counter the applied voltage in a DC motor or a DC generator.
- Applied voltage is defined as the voltage that is delivered across the load.
- Commutation is the positioning of the DC generator brushes so that the commutator segments change brushes at the same time the armature current changes direction.
- In a DC generator, commutation provides for the conversion of AC to a DC output that is generated in the armature windings.

DC EQUIPMENT CONSTRUCTION

Direct current machines are energy transfer devices. These machines can function as either a motor or a generator. DC motors and generators have the same basic construction, differing primarily in the energy conversion. To better understand the operation and construction of DC machines, a few basic terms must be understood.

EO 1.4 **STATE** the purpose of each of the following components of a DC machine:

a. Armature

b. Rotor

c. Stator

d. Field

Armature

The purpose of the *armature is* to provide the energy conversion in a DC machine (refer to Figure 2).

In a DC generator, the armature is rotated by an external mechanical force, such as a steam turbine. This rotation induces a voltage and current flow in the armature. Thus, the armature converts mechanical energy to electrical energy.

In a DC motor, the armature receives voltage from an outside electrical source and converts electrical energy into mechanical energy in the form of torque.

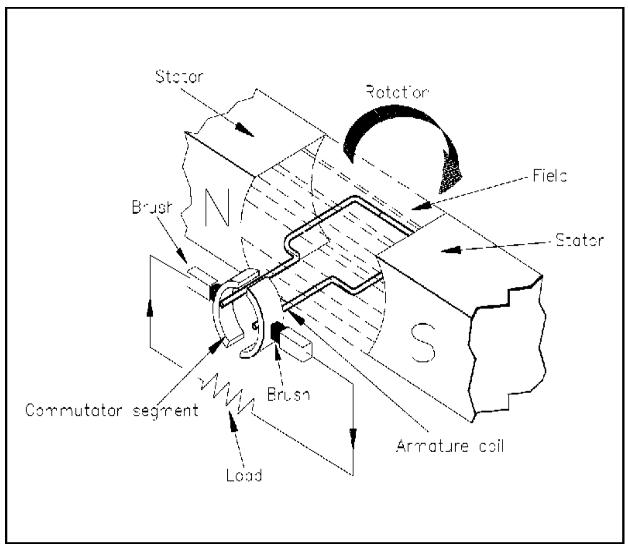

Figure 2 Basic DC Machine

Rotor

The purpose of the *rotor is* to provide the rotating element in a DC machine (refer to Figure 2). In a DC generator, the rotor is the component that is rotated by an external force. In a DC motor, the rotor is the component that turns a piece of equipment. In both types of DC machines, the rotor is the armature.

Stator

The *stator* is the part of a motor or generator that is stationary (refer to Figure 2). In DC machines, the purpose of the stator is to provide the magnetic field. The stator in Figure 2 is provided by a permanent magnet.

Field

The purpose of the *field* in a DC machine is to provide a magnetic field for producing either a voltage (generator) or a torque (motor) (refer to Figure 2). The field in a DC machine is produced by either a permanent magnet or an electromagnet. Normally, electromagnets are used because they have an increased magnetic strength, and the magnetic strength is more easily varied using external devices. In Figure 2, the field is provided by the stator.

Summary

The construction of DC equipment is summarized below.

DC Equipment Construction Summary

- The purpose of the armature is to provide the energy conversion in a DC machine.
- The purpose of the rotor is to provide the rotating element in a DC machine.
- In DC machines, the purpose of the stator is to provide the field.
- The purpose of the field in a DC machine is to provide a magnetic field for producing either a voltage or a torque.

DC GENERATOR THEORY

DC generators are widely used to produce a DC voltage. The amount of voltage produced depends on a variety of factors.

EO 1.5 **LIST** the three conditions necessary to induce a voltage into a conductor.

EO 1.6 Using the left-hand rule of generators, **DETERMINE** the direction of the magnetic field, the motion of the conductor, or the direction of current induced into a conductor.

EO 1.7 **DESCRIBE** how terminal voltage of a DC generator is adjusted.

EO 1.8 **STATE** the basis behind each of the four DC generator ratings.

EO 1.9 **LIST** the four internal losses found in a DC generator.

Voltage Production

Recall from Module 3, DC Circuits, that there are three conditions necessary to induce a voltage into a conductor.

1. A magnetic field
2. A conductor
3. Relative motion between the two

A DC generator provides these three conditions to produce a DC voltage output.

Theory of Operation

A basic DC generator has four basic parts: (1) a magnetic field; (2) a single conductor, or loop; (3) a commutator; and (4) brushes (Figure 3). The magnetic field may be supplied by either a permanent magnet or an electromagnet. For now, we will use a permanent magnet to describe a basic DC generator.

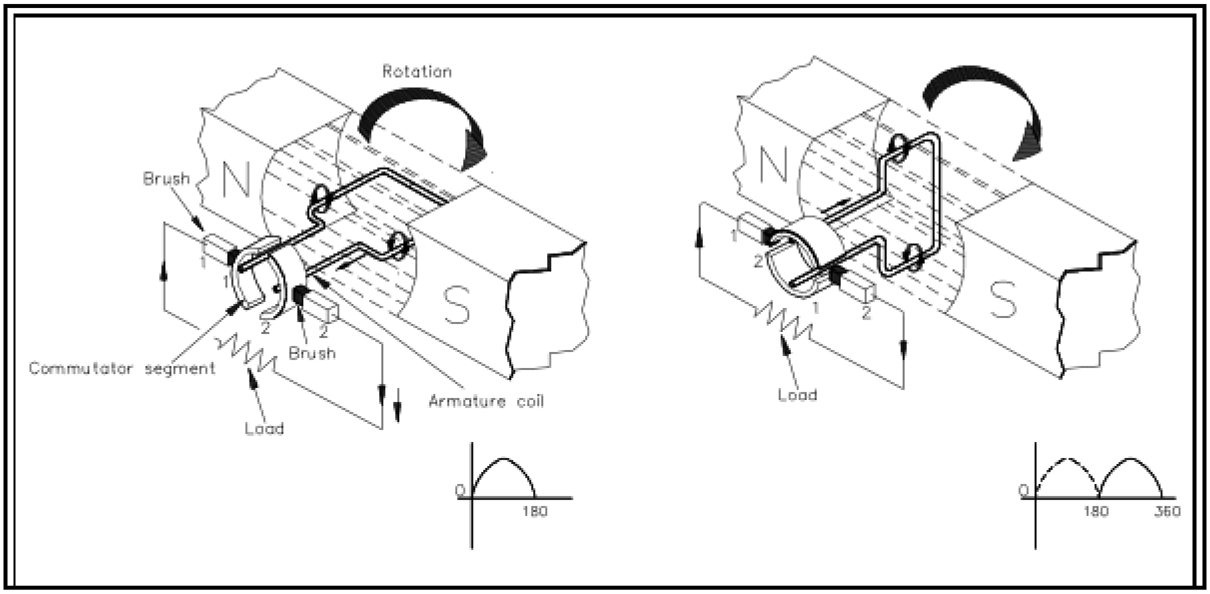

Figure 3 Basic Operation of a DC Generator

A single conductor, shaped in the form of a loop, is positioned between the magnetic poles. As long as the loop is stationary, the magnetic field has no effect (no relative motion). If we rotate the loop, the loop cuts through the magnetic field, and an EMF (voltage) is induced into the loop.

When we have relative motion between a magnetic field and a conductor in that magnetic field, and the direction of rotation is such that the conductor cuts the lines of flux, an EMF is induced into the conductor. The magnitude of the induced EMF depends on the field strength and the rate at which the flux lines are cut, as given in equation (5-1). The stronger the field or the more flux lines cut for a given period of time, the larger the induced EMF.

$$E_g = K\Phi N \quad (5\text{-}1)$$

where

E_g = generated voltage

K = fixed constant

Φ = magnetic flux strength

N = speed in RPM

The direction of the induced current flow can be determined using the "left-hand rule" for generators. This rule states that if you point the index finger of your left hand in the direction of the magnetic field (from North to South) and point the thumb in the direction of motion of the conductor, the middle finger will point in the direction of current flow (Figure 4). In the generator shown in Figure 4, for example, the conductor closest to the N pole is traveling upward across the field; therefore, the current flow is to the right, lower corner. Applying the left-hand rule to both sides of the loop will show that current flows in a counter-clockwise direction in the loop.

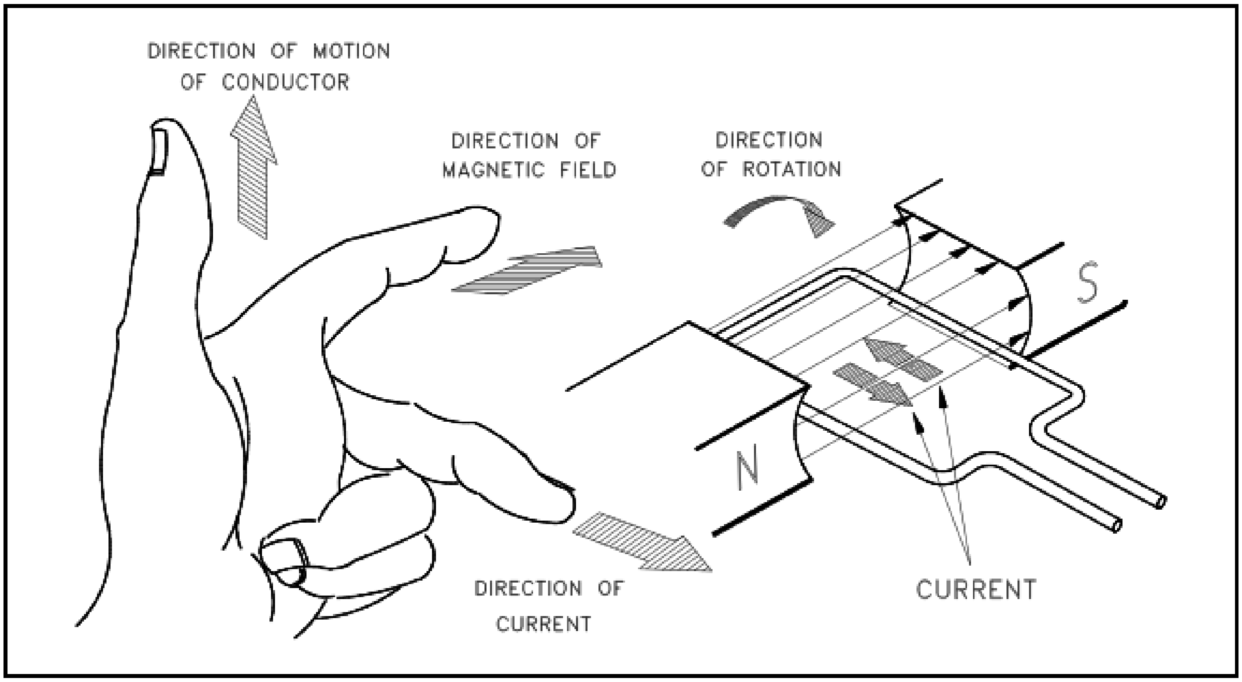

Figure 4 Left-Hand Rule for Generators

Commutator Action

The commutator converts the AC voltage generated in the rotating loop into a DC voltage. It also serves as a means of connecting the brushes to the rotating loop. The purpose of the brushes is to connect the generated voltage to an external circuit. In order to do this, each brush must make contact with one of the ends of the loop. Since the loop or armature rotates, a direct connection is impractical. Instead, the brushes are connected to the ends of the loop through the commutator.

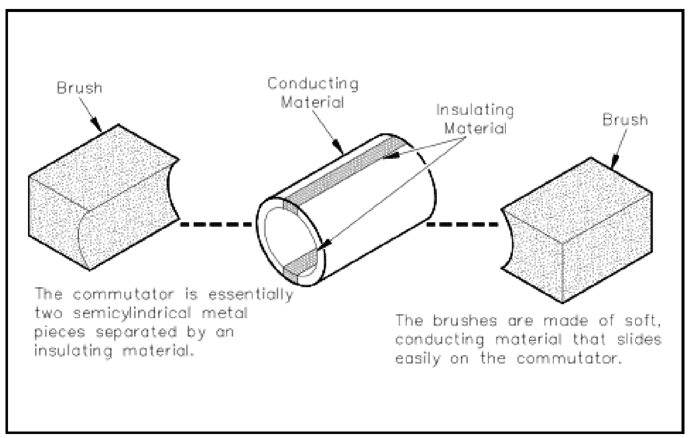

Figure 5 Commutator Segments and Brushes

In a simple one-loop generator, the commutator is made up of two semicylindrical pieces of a smooth conducting material, usually copper, separated by an insulating material, as shown in Figure 5. Each half of the commutator segments is permanently attached to one end of the rotating loop, and the commutator rotates with the loop. The brushes, usually made of carbon, rest against the commutator and slide along the commutator as it rotates. This is the means by which the brushes make contact with each end of the loop.

Each brush slides along one half of the commutator and then along the other half. The brushes are positioned on opposite sides of the commutator; they will pass from one commutator half to the other at the instant the loop reaches the point of rotation, at which point the voltage that was induced reverses the polarity. Every time the ends of the loop reverse polarity, the brushes switch from one commutator segment to the next. This means that one brush is always positive with respect to another. The voltage between the brushes fluctuates in amplitude (size or magnitude) between zero and some maximum value, but is always of the same polarity (Figure 6). In this manner, commutation is accomplished in a DC generator.

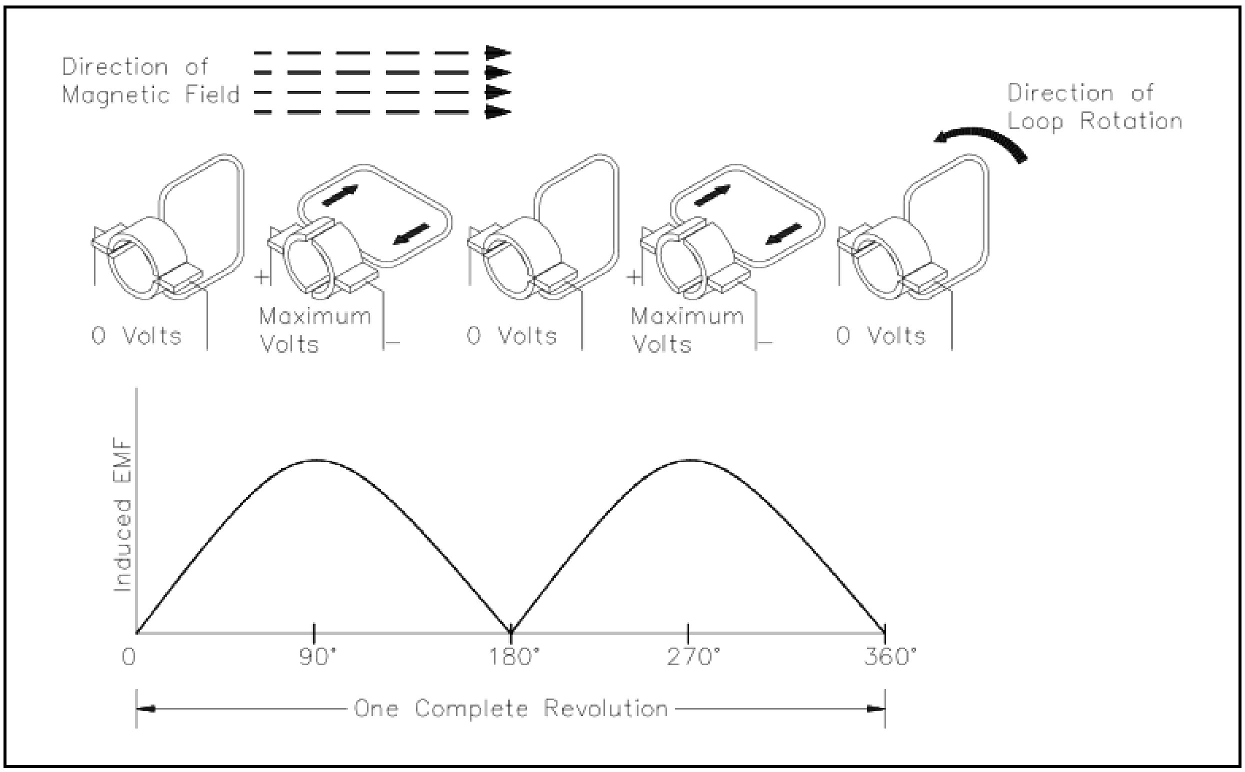

Figure 6 Commutation in a DC Generator

One important point to note is that, as the brushes pass from one segment to the other, there is an instant when the brushes contact both segments at the same time. The induced voltage at this point is zero. If the induced voltage at this point were not zero, extremely high currents would be produced due to the brushes shorting the ends of the loop together. The point at which the brushes contact both commutator segments, when the induced voltage is zero, is called the "neutral plane."

Field Excitation

The magnetic fields in DC generators are most commonly provided by electromagnets. A current must flow through the electromagnet conductors to produce a magnetic field. In order for a DC generator to operate properly, the magnetic field must always be in the same direction. Therefore, the current through the field winding must be direct current. This current is known as the *field excitation current* and can be supplied to the field winding in one of two ways. It can come from a separate DC source external to the generator (e.g., a separately excited generator) or it can come directly from the output of the generator, in which case it is called a *self-excited generator.*

In a self-excited generator, the field winding is connected directly to the generator output. The field may be connected in series with the output, in parallel with the output, or a combination of the two.

Separate excitation requires an external source, such as a battery or another DC source. It is generally more expensive than a self-excited generator. Separately excited generators are, therefore, used only where self-excitation is not satisfactory. They would be used in cases where the generator must respond quickly to an external control source or where the generated voltage must be varied over a wide range during normal operations.

Terminal Voltage

DC generator output voltage is dependent on three factors (recall equation 5-1): (1) the number of conductor loops in series in the armature, (2) armature speed, and (3) magnetic field strength. In order to change the generator output, one of these three factors must be varied. The number of conductors in the armature cannot be changed in a normally operating generator, and it is usually impractical to change the speed at which the armature rotates. The strength of the magnetic field, however, can be changed quite easily by varying the current through the field winding. This is the most widely used method for regulating the output voltage of a DC generator (Figure 7).

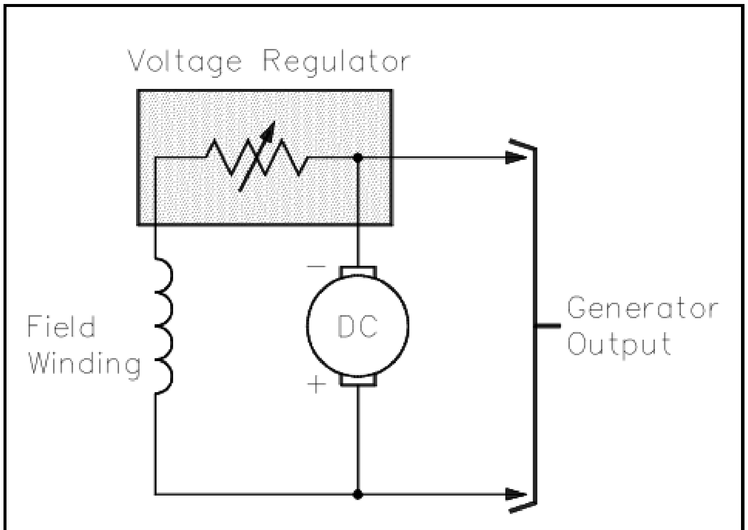

Figure 7 Varying Generator Terminal Voltage

DC Generator Ratings

A DC generator contains four ratings.

Voltage: Voltage rating of a machine is based on the insulation type and design of the machine.

Current: The current rating is based on the size of the conductor and the amount of heat that can be dissipated in the generator.

Power: The power rating is based on the mechanical limitations of the device that is used to turn the generator and on the thermal limits of conductors, bearings, and other components of the generator.

Speed: Speed rating, at the upper limit, is determined by the speed at which mechanical damage is done to the machine. The lower speed rating is based on the limit for field current (as speed increases, a higher field current is necessary to produce the same voltage).

Internal Losses

There are four internal losses that contribute to lower efficiency of a DC generator.

- Copper losses
- Eddy-current losses
- Hysteresis losses
- Mechanical losses

Each of these is described in the paragraphs that follow.

Copper Losses

Copper loss is the power lost as heat in the windings; it is caused by the flow of current through the coils of the DC armature or DC field. This loss varies directly with the square of the current in the armature or field and the resistance of the armature or field coils.

Armature: $I_a^2 R_a$

Field: $I_f^2 R_f$

Eddy-Current Losses

As the armature rotates within the field, it cuts the lines of flux at the same time that the copper coils of wire that are wound on the armature cut the lines of flux. Since the armature is made of iron, an EMF is induced in the iron, which causes a current to flow. These circulating currents within the iron core are called *eddy-currents.*

To reduce eddy-currents, the armature and field cores are constructed from laminated (layered) steel sheets. The laminated sheets are insulated from one another so that current cannot flow from one sheet to the other.

Hysteresis Losses

Hysteresis losses occur when the armature rotates in a magnetic field. The magnetic domains of the armature are held in alignment with the field in varying numbers, dependent upon field strength. The magnetic domains rotate, with respect to the particles not held in alignment, by one complete turn during each rotation of the armature. This rotation of magnetic domains in the iron causes friction and heat. The heat produced by this friction is called magnetic hysteresis loss.

To reduce hysteresis losses, most DC armatures are constructed of heat-treated silicon steel, which has an inherently low hysteresis loss. After the heat-treated silicon steel is formed to the desired shape, the laminations are heated to a dull red and then allowed to cool. This process, known as annealing, reduces hysteresis losses to a very low value.

Mechanical Losses

Rotational or *mechanical losses* can be caused by bearing friction, brush friction on the commutator, or air friction (called windage), which is caused by the air turbulence due to armature rotation. Careful maintenance can be instrumental in keeping bearing friction to a minimum. Clean bearings and proper lubrication are essential to the reduction of bearing friction. Brush friction is reduced by assuring proper brush seating, using proper brushes, and maintaining proper brush tension. A smooth and clean commutator also aids in the reduction of brush friction.

Summary

DC generator theory is summarized below.

DC Generator Theory Summary

- The three conditions necessary to induce a voltage into a conductor are:
  - Magnetic field
  - Conductor
  - Relative motion between the two
- The left-hand rule states that if you point the index finger of the left hand in the direction of the magnetic field and point the thumb in the direction of motion of the conductor, the middle finger will point in the direction of current flow.
- The terminal voltage of a DC generator is adjusted by varying the field strength.
- The voltage rating of a DC generator is based on the insulation type and design of the machine.
- The current rating of a DC generator is based on the size of the conductor and the amount of heat that can be dissipated in the generator.
- The power rating of a DC generator is based on the mechanical limitation of the device that is used to turn the generator.
- The upper speed rating of a DC generator is determined by the speed at which mechanical damage is done to the machine. The lower speed rating is based on the limit for field current.
- There are four internal losses that contribute to lower efficiency of a DC generator.
  - Copper losses
  - Eddy-current losses
  - Hysteresis losses
  - Mechanical losses

DC GENERATOR CONSTRUCTION

A DC generator may be constructed in a variety of ways depending upon the relationship and location of each of the fields. Each type of construction contains certain advantages.

EO 1.10 **DESCRIBE** the differences in construction between a shunt-wound and a series-wound DC generator with respect to the relationship between the field and the armature.

EO 1.11 **DESCRIBE** the relationship between the shunt and series fields for cumulatively-compounded and differentially-compounded DC generators

EO 1.12 **DESCRIBE** the voltage-vs-load current characteristics for a flat-compounded, over-compounded, and under-compounded DC generator.

Shunt-Wound DC Generators

When the field winding of a generator is connected in parallel with the generator armature, the generator is called a shunt-wound generator (Figure 8).

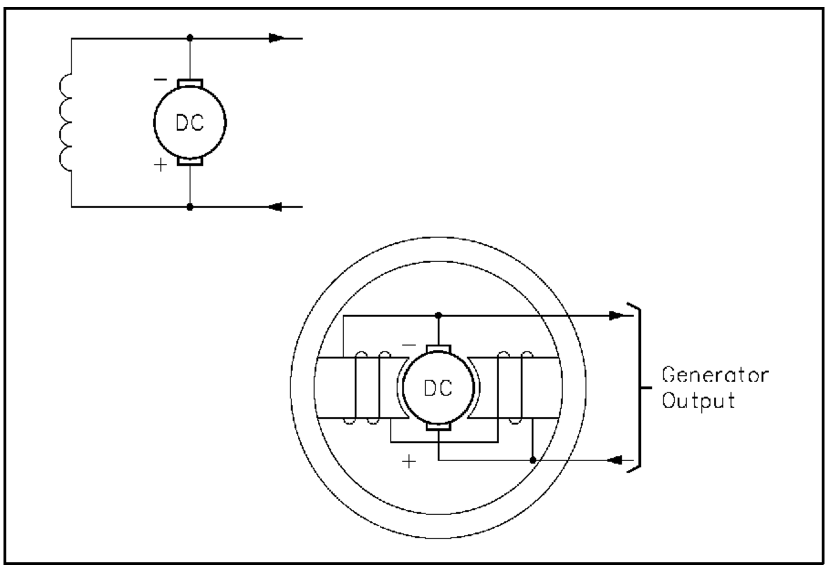

Figure 8 Shunt-Wound DC Generator

The excitation current in a shunt-wound generator is dependent upon the output voltage and the field resistance. Normally, field excitation is maintained between 0.5 and 5 percent of the total current output of the generator.

The shunt-wound generator, running at a constant speed under varying load conditions, has a much more stable voltage output than does a series-wound generator. Some change in output voltage does take place. This change is caused by the fact that, as the load current increases, the voltage drop (I_aR_a) across the armature coil increases, causing output voltage to decrease. As a result, the current through the field decreases, reducing the magnetic field and causing voltage to decrease even more. If load current is much higher than the design of the generator, the drop in output voltage is severe. For load current within the design range of the generator, the drop in output voltage is minimal (Figure 9).

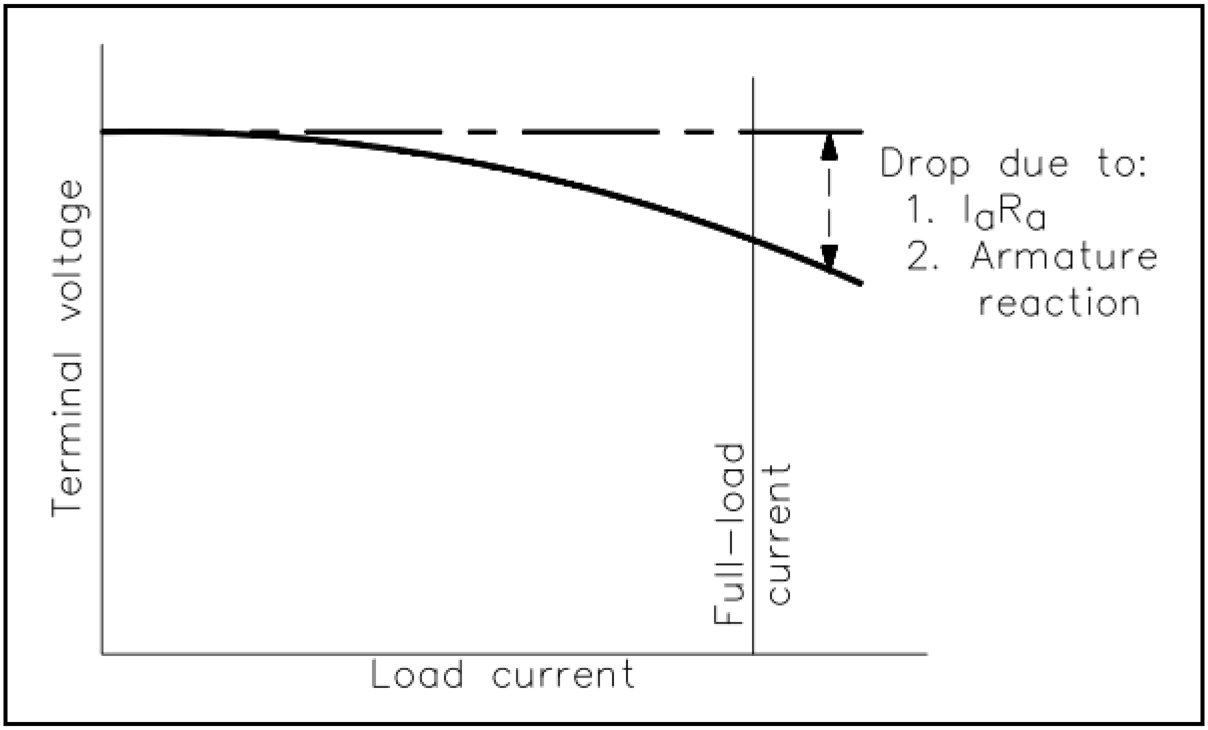

Figure 9 Output Voltage-vs-Load Current for Shunt-Wound DC Generator

Series-Wound DC Generators

When the field winding of a DC generator is connected in series with the armature, the generator is called a series-wound generator (Figure 10).

The excitation current in a series-wound generator is the same as the current the generator delivers to the load. If the load has a high resistance and only draws a small amount of current, the excitation current is also small.

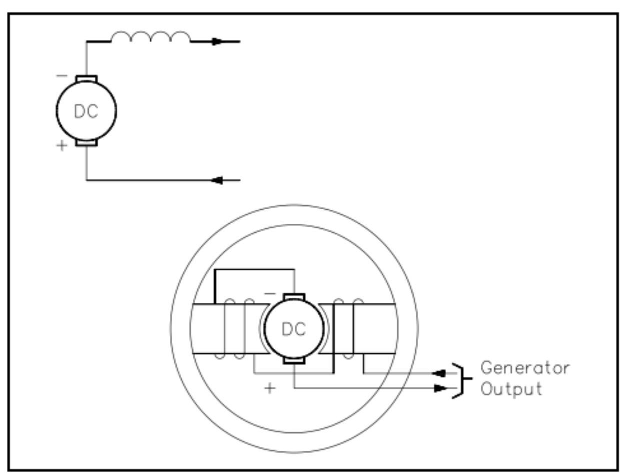

Figure 10 Series-Wound DC Generator

Therefore, the magnetic field of the series field winding is weak, making the generated voltage low. Conversely, if the load draws a large current, the excitation current is also high. Therefore, the magnetic field of the series field winding is very strong, and the generated voltage is high.

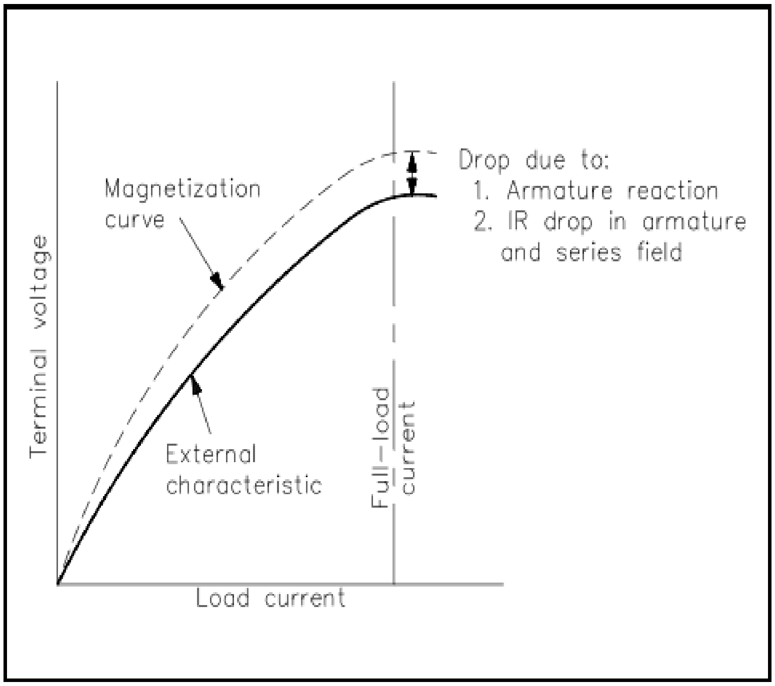

Figure 11 Output Voltage-vs-Load Current for Series-Wound DC Generator

As you can see in Figure 11, in a series generator, changes in load current drastically affect the generator output voltage. A series generator has poor voltage regulation, and, as a result, series generators are not used for fluctuating loads. As is the case for the shunt-wound generator, a series-wound generator also exhibits some losses due to the resistance of the windings and armature reaction. These losses cause a lower terminal voltage than that for an ideal magnetization curve.

Compound Generators

Series-wound and shunt-wound generators have a disadvantage in that changes in load current cause changes in generator output voltage. Many applications in which generators are used require a more stable output voltage than can be supplied by a series-wound or shunt-wound generator. One means of supplying a stable output voltage is by using a compound generator.

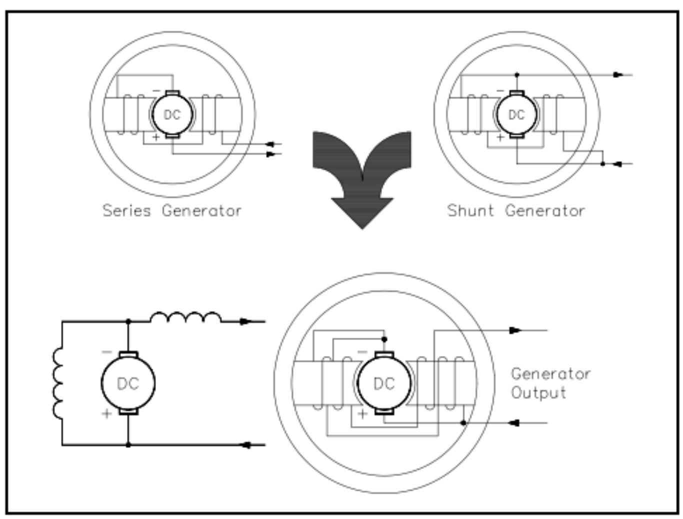

Figure 12 Compounded DC Generator

The compound generator has a field winding in parallel with the generator armature (the same as a shunt-wound generator) and a field winding in series with the generator armature (the same as a series-wound generator) (Figure 12).

The two windings of the compounded generator are made such that their magnetic fields will either aid or oppose one another.

If the two fields are wound so that their flux fields oppose one another, the generator is said to be *differentially-compounded.* Due to the nature of this type of generator, it is used only in special cases and will not be discussed further in this text.

If the two fields of a compound generator are wound so that their magnetic fields aid one another, the generator is said to be *cumulatively-compounded.* As the load current increases, the current through the series field winding increases, increasing the overall magnetic field strength and causing an increase in the output voltage of the generator. With proper design, the increase in the magnetic field strength of the series winding will compensate for the decrease in shunt field strength. Therefore, the overall strength of the combined magnetic fields remains almost unchanged, so the output voltage will remain constant. In reality, the two fields cannot be made so that their magnetic field strengths compensate for each other completely. There will be some change in output voltage from the no-load to full-load conditions.

In practical compounded generators, the change in output voltage from no-load to full-load is less than 5 percent. A generator with this characteristic is said to be *flat-compounded* (Figure 13).

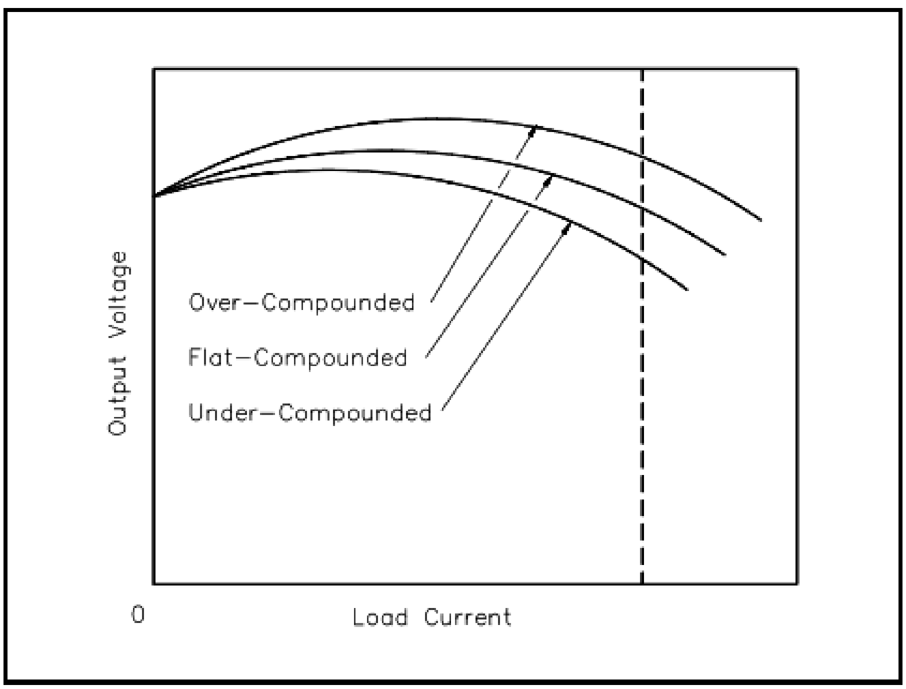

Figure 13 Voltage-vs-Current for a Compounded DC Generator

For some applications, the series winding is wound so that it overcompensates for a change in the shunt field. The output gradually rises with increasing load current over the normal operating range of the machine. This type of generator is called an *over-compounded* generator. The series winding can also be wound so that it undercompensates for the change in shunt field strength. The output voltage decreases gradually with an increase in load current. This type of generator is called an *under-compounded* generator.

Summary

DC generator construction is summarized below.

DC Generator Construction Summary

- A shunt-wound DC generator is constructed so that the field winding is in parallel with the armature winding.
- The voltage of a shunt-wound DC generator decreases with an increase in load current.
- A series-wound DC generator is constructed so that the field winding is in series with the armature winding.
- The voltage of a series-wound DC generator increases sharply with an increase in load.
- In a cumulatively-compounded DC generator, the series and shunt fields aid one another.
- In a differentially-compounded DC generator, the series and shunt fields oppose one another.
- The voltage of a flat-compounded DC generator changes less than 5 percent from no-load to full-load.
- The voltage of an over-compounded DC generator gradually rises with an increasing load.